

The Relationship Between the Physical, Optical and Electromagnetic Properties of Arctic Snow and Sea Ice with Special Reference to the Influence of Entrapped Materials

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LONG TERM GOAL

My long term goal is to investigate the effects of and change in environmental conditions on the optical, thermal, microwave and physical properties of snow and sea ice, and then to improve the ability to invert electromagnetic signature information to sea ice physical properties.

SCIENTIFIC OBJECTIVES

The objectives of this project were to:

- investigate the relationships between the physical (temperature, salinity, crystal structure, inclusions) and electromagnetic (optical and microwave) properties of natural sea ice;
- model the first order effects of inclusions on the thermal, optical, and microwave properties;
- model the second order effects of inclusions on the physical properties;
- apply these models to compare predicted melting rates and change in SAR signatures.

APPROACH

A comprehensive field experiment was conducted during April/May 1994 on landfast ice near Barrow, Alaska. My contribution to the ARI-EM multidisciplinary program was to measure the active microwave properties of sea ice and snow at various ice study sites (Perovich et al. and Grenfell et al., submitted). A special studies project was conducted in collaboration with C. Roesler (UConn) to study sites which revealed high concentrations of entrapped material. The specific goal of this grant was to study the interrelationships between the presence of small embedded particles and their impact on the structure of sea ice and its electromagnetic properties (e.g. optical and microwave).

The microwave behavior was documented *in situ* using an instrumentation radar which operated both monostatically (10 GHz, Quad-Pol, 10°-50° incidence angle) and bistatically (0.5 to 12 GHz, HH-Pol, 20°-45° incidence angle). Backscatter intensity as a function of position from the radar was recorded to later be compared with the physical property profile information.

Ice cores were collected and processed by Roesler for a number of locations at the two major field sites. Processing included temperature profiles (5 cm resolution); vertical and horizontal thin sections for crystal size distribution and large scale inclusion distribution; salinity profile; particle composition and size distribution; chlorophyllic pigments; dissolved absorption spectra; and particulate absorption spectra (See Roesler's report).

All measurements were conducted within a pre-defined area. *In situ* measurements were first made of the undisturbed scene with the snow cover in place. The snow layer was then removed from half of the study area and then the measurements were repeated. Variability in the surface ice, due to particulate material in the upper 10 cm, was observed once snow was removed. Six sites ranging from optically clear to particle laden ice were then selected to investigate the influence of particulate matter on ice properties.

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The goal of Roesler's program was to apply a simple static model to predict the influence of absorbing materials on the thermal properties of sea ice (Roesler and Iturriaga, 1994). The increase in temperature within the ice relative to a reference sample, ΔT [$^{\circ}$ C], was modeled from:

$$\Delta T(z) = \frac{\Delta a(z) E(z) t}{\rho c_{si}} \quad (1)$$

where Δa is the difference in the absorption coefficient due to the entrapped material over that of pure ice, E is the spectral irradiance incident on the ice surface, t is the time period of solar heating, ρ is the density of sea ice and c_{si} is the specific heat of sea ice. Concurrent with the change in temperature is a predicted change in ice crystal structure, dielectric constant, and wideband (0.5 to 14GHz) scattering enhancement (Roesler and Onstott; Onstott and Roesler^a, submitted). Changes in ice physical properties have been documented and are included in the above paper set.

A second, smaller scale field program was conducted in 1995 in early April and early June to complement the 1994 measurements (Perovich et al., 1997). The goal of this field effort was to investigate the relationship between airborne particulate material and the optical, thermal and microwave properties of snow (Onstott and Roesler^b, in prep.), and the association of particle concentration on regional melt rates. Transects of 1-1.5 km in length ran perpendicular to the coast line were conducted by Roesler at 25 m resolution at three sites (Browerville, NARL, NARL runway). Snow thickness, snow/ice interface temperature, snow particle concentration and absorption were measured in April. Snow, slush, and surface water depths were measured were in June. SAR imagery were collected and analyzed by Onstott for the period of early April through late July. Using the same approach described above, the increase in snow temperature due to the enhanced absorption by the airborne particulate material can be estimated for the springtime melt period. Based upon the particle distributions determined along the transects in April, melting rates will be estimated and compared with the changes in SAR backscatter (σ_0).

WORK COMPLETED

Data analyses and model building efforts are completed. Final drafts of the remaining papers from this program are being circulated to co-authors.

RESULTS

The presence of particles are found to have a dramatic impact on the physical properties of sea ice and are found to modify the electromagnetic behavior both optically and in the microwave (not necessarily expected). Particle concentrations were found to vary by three orders of magnitude for the six sites studied. Particles were observed in large inclusions several millimeters in diameter suggesting that embedded material aggregates as the ice ages and/or with the return of direct solar irradiance during spring. The heat trapping associated with the absorbing particles produced a temperature profile which was warmer by up to 3 $^{\circ}$ C at a time of year when the ice surface temperature is above -10 $^{\circ}$ C and warming (Fig. 1a,b). This temperature difference produced up to a 32% change in dielectric constant (Fig. 1c,d) which results in up to a 1.2 dB change in surface reflectivity. In addition, the number and large size of particles (Fig. 1e) was sufficient to produce a several dB change in backscatter intensity (Fig. 1f), even though the propagation loss at microwave frequencies has increased substantially. Modification of snow-ice interface roughness was also noted.

A multi-component theoretical model was developed which incorporates optical, microwave, thermal and physical properties of snow and sea ice (Fig. 2). Inputs include

particle size distribution and absorption coefficients, and standard sea ice physical property coefficients. Property change predictions may be made in association with the seasonal variation in solar irradiance. The ice profile properties are then used to predict apparent optical and microwave properties. This model includes a non-linear growth model which is based on (a) interactive solutions of surface energy balance and heat conduction, (b) non-linear feedback associated with brine mechanisms, and (c) fine time and vertical resolution in the finite-difference module to predict ice temperature profile and growth rates.

The airborne particles from a populated area (Browerville, Alaska) were found to be concentrated downwind and deposited on the ice surface and in the snow. The distribution of particles generally decreased offshore, except for local maxima associated with ridges which trapped airborne particles. The concentration of particles, snow/ice interface temperature, and area of snow melt water correlate well. It also appears that the correlation with SAR backscatter is high (Fig. 3). Direct observations and SAR imagery from June confirms that regions with enhanced particle distributions exhibited accelerated melting rates, as predicted. Particle laden and free areas are found to show a different temporal response (Fig. 3b).

IMPACT/APPLICATION

This project is focused on the role of marine-derived and airborne particles on the physical, electromagnetic and thermodynamic properties of snow and sea ice. The variation in these properties observed in natural conditions is quite significant. Process linkages are also clearly defined. These results indicate that such processes should be included in thermodynamic models of polar regions as the impact of particles results in enhanced melting rates and more ice free days per season, potentially. A dramatic increase in the concentration and distribution of "dirty" ice in the Arctic has been reported (S. Martin, A. Gow, T. Tucker pers. comm.).

TRANSITIONS

None.

RELATED PROJECTS

The integrated electromagnetic-thermodynamic model is currently being used to predict ice growth rates and thickness for landfast ice off of Cape Roberts (Antarctica) in support of an international sediment drilling program (funded by NSF).

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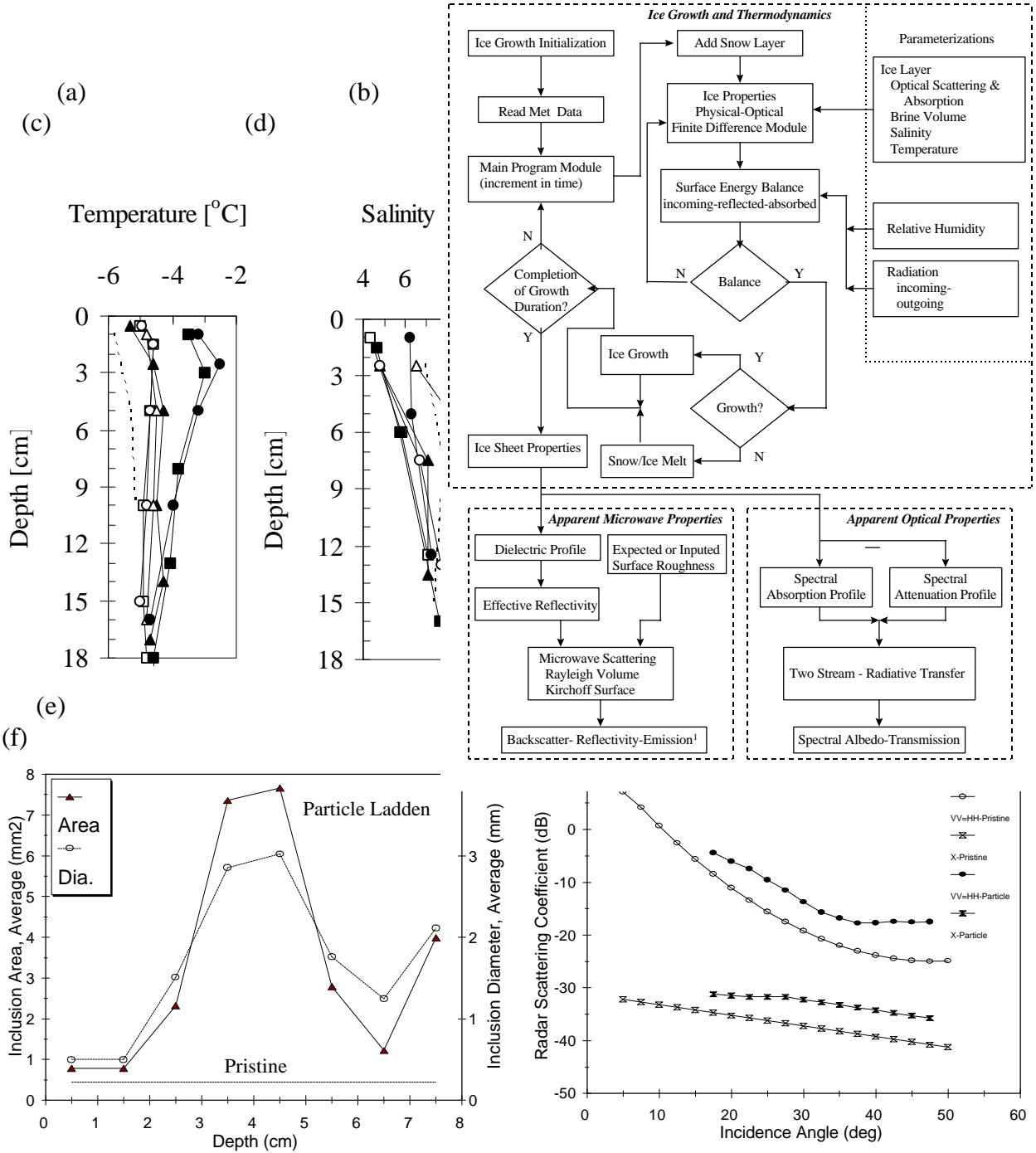


Figure 1. Characteristics of sea ice sampled during April 1994. Measured temperature (a) and salinity (b, and predicted complex dielectric constant profiles (c,d) are presented for the six study sites. The inclusion size and area histogram for one of the particle-ladden sites is also shown (e). Measured backscatter at 10 GHz is shown for both the particle and particle-free areas (f). Closed symbols indicate particle-ladden ice, open symbols indicate pristine conditions.

Figure 2. Multi-component theoretical model incorporates optical, microwave, thermal and physical properties of snow and sea ice (e.g. particle size distribution, absorption coefficients, and standard sea ice physical property coefficients). Predictions may be made of property changes associated with the season variation in solar radiation, ice growth rates, and snow melt rates. The non-linear growth model is based on solving the surface energy balance and heat conduction, and incorporates non-linear feedbacks (e.g. due to brine mechanisms). Fine time steps and vertical resolutions are facilitated by the finite-difference model in the prediction of temperature profile and ice growth rate.

(a)

(b)

Figure 3. SAR images of Barrow, Alaska (a). Black lines indicate approximate locations of transects immediate to (top) and away from (bottom) Browerville. Backscatter cross sections are for sites indicated by white boxes in (a) . The temporal response at these sites is shown in (b). The filled markers for the sites with the greatest particle concentrations. The size of the marker provides indication of concentration. The open markers are for the sites which are more pristine. The temporal response for the particle ladden and free sites show different behaviors, especially early spring and at peak melt.

